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THE ACS LCID PROJECT: RR LYRAE STARS AS TRACERS OF OLD POPULATION GRADIENTS IN THE ISOLATED DWARF SPHEROIDAL GALAXY TUCANA¹

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ABSTRACT

We present a study of the radial distribution of RR Lyrae variables, which present a range of photometric and pulsational properties, in the dwarf spheroidal galaxy Tucana. We find that the fainter RR Lyrae stars, having a shorter period, are more centrally concentrated than the more luminous, longer period RR Lyrae variables. Through comparison with the predictions of theoretical models of stellar evolution and stellar pulsation, we interpret the fainter RR Lyrae stars as a more metal-rich subsample. In addition, we show that they must be older than about 10 Gyr. Therefore, the metallicity gradient must have appeared very early on in the history of this galaxy.

Subject headings: galaxies: dwarf — galaxies: individual (Tucana) — Local Group — stars: horizontal-branch — stars: variables: other

Online material: color figures

1. INTRODUCTION

The oldest stellar populations in galaxies are of fundamental importance because they can constrain the epoch of onset of star formation in the universe. Unfortunately, the oldest main-sequence turn-offs (MSTO), which provide the most straightforward characterization of the old population, can only be reached in a handful of Milky Way satellite galaxies using current ground-based observing facilities. An alternative approach is the characterization of the RR Lyrae star populations. The fact that the properties of the RR Lyrae stars reflect the properties of the old population is crucial because the horizontal-branch (HB) stars are about 3 magnitudes brighter than their MSTO counterpart.

For example, it has long been suspected that the mean magnitude of the RR Lyrae variables, $M_V(\text{RR})$, is a function of $[\text{Fe}/\text{H}]$, in the sense that more metal-poor RR Lyrae stars are more luminous (Sandage 1958). The correlation between $M_V(\text{RR})$ and $[\text{Fe}/\text{H}]$ was later confirmed by stellar evolution models, but with the additional constraint that the morphology of the HB, i.e., the evolutionary status of the stellar population, must be taken into account (e.g., Cassisi et al. 2004). As the population gets older, the mass of the stars reaching the HB decreases, giving a bluer HB. In this case, the stars crossing

the instability strip (IS) are therefore already evolving off the zero-age horizontal branch (ZAHB) and are more luminous than younger stars of the same metallicity.

In addition, observations of Galactic globular clusters suggested that the lower their metallicity, the longer the mean period of their RR Lyrae stars. This led to the various period-metallicity relations found in the literature (see, e.g., Catelan 1992; Sandage 1993; Sarajedini et al. 2006), or the more elaborate period-metallicity-amplitude relations (e.g., Alcock et al. 2000; Sandage 2004), providing a convenient way of estimating the metallicity of a stellar system based on distance- and reddening-free observables (namely, mean period $\langle P_{ab} \rangle$ and visual amplitude A_V).

We note, though, that Clement & Shelton (1999) have argued that the period-amplitude (P-A) relation for RRab stars is not a function of metal abundance, but is instead related to the evolutionary status of the RR Lyrae stars. In the metal-poor, Oosterhoff type II clusters, the (blue) HB stars would have started to evolve away from the ZAHB, crossing the IS at higher luminosities, therefore following a different P-A relation from the ZAHB RR Lyrae stars.

However, theoretical (Bono et al. 2007) and observational (Wehlau et al. 1999; Kaluzny et al. 2000; Layden & Sarajedini 2000; Olech et al. 2001; Borissova et al. 2001) evidence suggest that, while there is a clear correlation of Oosterhoff type with metallicity, there is an additional dependence of the period at a given amplitude on metallicity, with the more metal-rich stars having shorter periods.

An analysis of the variation of these observables as a function of the position within a galaxy can highlight the eventual radial trends across the studied galaxy. This, in turn, provides important clues to the formation mechanisms and the star formation history of the host galaxy. Hence, by providing information about the properties of the underlying population, variable star research procures a way to study the histories of these galaxies, independent of and complementary to the CMD analysis.

In this Letter we report, for the first time, the detection of stellar population gradients in a dwarf galaxy based solely on the periods and luminosities of its RR Lyrae stars. This was made possible by the large number of RR Lyrae variables discovered in the isolated Local Group dSph Tucana, based on *Hubble Space Telescope* (HST) ACS data covering the whole

¹ Based on observations made with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. These observations are associated with program 10505.

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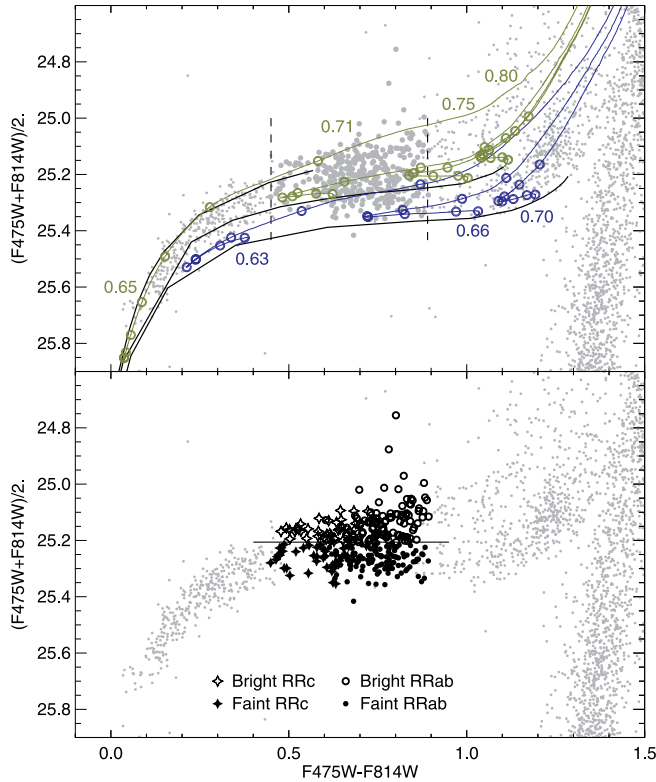


FIG. 1.—Zoom-in on the HB of Tucana. *Top*: The RR Lyrae stars are overplotted with larger dots. The solid black lines represent, from top to bottom, the $Z = 0.0001$, 0.0003 , and 0.001 ZAHB. The green and blue lines are evolutionary tracks with $Z = 0.0003$ and $Z = 0.001$, respectively, and masses as labeled. Overplotted on them, the circles indicate intervals of 10 Myr. ZAHB loci and tracks are solar-scaled models from the BaSTI library (Pietrinferni et al. 2004), plotted assuming $A_g = 0.122$ and $A_i = 0.061$ from NASA/IRSA (<http://irsa.ipac.caltech.edu/applications/DUST/>) and $(m - M)_0 = 24.84$ (C. Gallart et al. 2008, in preparation). The vertical dashed lines roughly delimit the IS. *Bottom*: Different symbols have been used for each type and subsample of RR Lyrae variables, as labeled in the figure. For the sake of clarity, RRd are not represented. The horizontal line shows the mean intensity-weighted magnitude of all the RR Lyrae stars.

body of the galaxy, together with the high quality of the light curves. We present supporting evidence from the different evolutionary phases present in the CMD.

2. OBSERVATIONS AND DATA REDUCTION

The present analysis is based on observations obtained with the Advanced Camera for Surveys on board the *HST* as part of the major program LCID¹¹ aiming at deriving detailed star formation histories for a sample of Local Group isolated dwarf galaxies (C. Gallart et al. 2008, in preparation). As the goal of these observations was to reach the oldest MTSO with good signal-to-noise ratio on the final stacked images, 32 orbits were devoted to the observations of Tucana. These were collected over about 5 consecutive days between 2006 April 25 and 30. As each orbit was devoted to one exposure in the F475W band and one in F814W, the observing sequence consisted of alternating ~ 1000 s exposures in F475W and F814W for an optimal sampling of the light curves. The DAOPHOT/ALLFRAME suite of programs (Stetson 1994) was used to obtain the instrumental photometry of the stars on

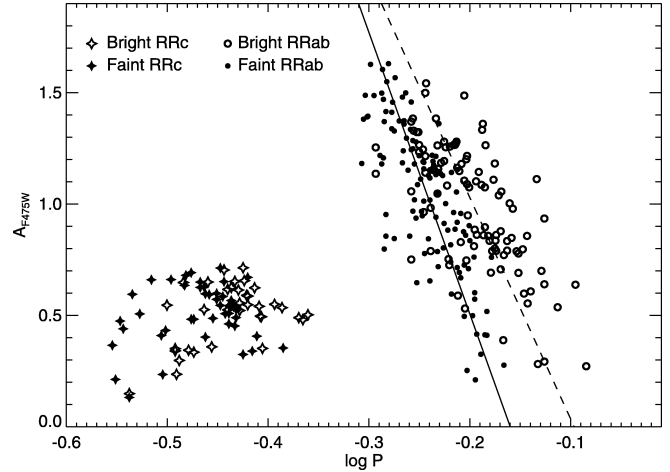


FIG. 2.—Period-amplitude diagram for the RR Lyrae stars in Tucana. Symbols are as in the bottom panel of Fig. 1. Linear fits to each sample of RRab are also represented.

the individual, nondrizzled images. A detailed description of the observations, data reduction, and calibration will be given in a forthcoming paper (M. Monelli et al. 2008, in preparation). To search for variable stars, the Welch-Stetson variability index (Welch & Stetson 1993) was used. From the list of candidates, 358 stars were identified as bona fide RR Lyrae stars, for which the period was searched through Fourier analysis following the prescription of Horne & Baliunas (1986). We identified 216 RRab, 82 RRc, and 60 RRd stars based on their period and light-curve shape. Further details about the variable star content of Tucana and another isolated dSph, Cetus, will be presented in a future paper (E. Bernard et al. 2008, in preparation).

3. THE RR LYRAE POPULATION AND ITS SPATIAL GRADIENTS

Figure 1 (*top*) shows the CMD of Tucana centered on the HB. The $(F475W + F814W)/2 \sim V$ filter combination was chosen for the ordinate axis so that the HB appears approximately horizontal. The RR Lyrae stars are overplotted with larger dots using their intensity-weighted magnitudes. One can see that Tucana harbors a rather complex HB, which is well populated on both sides of the IS. The red side also presents a small gap in magnitude, suggesting the combination of two HBs of different luminosities. This is supported by the unusual width in luminosity of the HB inside the IS (~ 0.3 mag at $F475W - F814W = 0.7$, excluding the few bright and faint outliers). As the evolutionary tracks show, in Figure 1 (*top*), a stellar population at a given metallicity does not span more than ~ 0.15 mag in brightness within the IS, even taking into account the evolution off the ZAHB.

We arbitrarily used the mean magnitude of the variables at $(F475W + F814W)/2 \sim 25.2$, shown with the horizontal line in the bottom panel of Figure 1, to split the RRab, RRc, and RRd variables into bright and faint subsamples, each type of variable having approximately the same number of stars in each subsample. Different symbols have been used for each type and subsample. For the sake of clarity, RRd variables are not represented.

The RR Lyrae stars are plotted on P-A diagram in Figure 2. The symbols are the same as in the bottom panel of Figure 1. Linear fits to each sample of RRab are also represented. We can clearly identify two distinct RRab sequences, characterized by different mean periods and dispersions around the fit. Based on their period distribution, we find a Kolmogorov-Smirnov

¹¹ Local Cosmology from Isolated Dwarfs, <http://www.iac.es/project/LCID/>

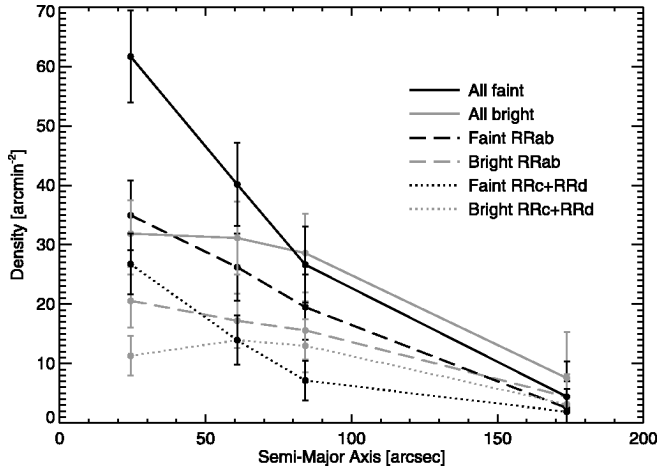


FIG. 3.—Radial distribution of the different subsamples of RR Lyrae stars in Tucana, showing how the fainter RR Lyrae stars are systematically more concentrated in the center of the galaxy than the brighter variables. The error bars correspond to Poisson statistics. [See the electronic edition of the *Journal* for a color version of this figure.]

(KS) discrepancy of $D_{\text{KS}} = 0.4397$, implying a probability $P_{\text{KS}} < 10^{-9}\%$ that the bright and faint RRab subsamples were drawn from the same parent population. As predicted by nonlinear pulsation models (Bono et al. 1997b), the mean period is a function of luminosity, in the sense that the more luminous variables tend to have a larger period. The period difference also shows up in the RRc subtype: the “bell shape” distribution (Bono et al. 1997b) of the brighter RRc is shifted toward longer period with respect to the fainter RRc. The difference in mean period is ~ 0.02 days ($P_{\text{KS}} < 0.34\%$). The mean primary period of double-mode RR Lyrae stars presents a similar shift between the bright and faint subsamples ($P_{\text{KS}} < 2 \times 10^{-5}\%$).

Interestingly, the faint and bright subsamples of RRab variables have mean periods of 0.574 and 0.640 respectively, which is very reminiscent of the mean periods of the Oosterhoff types I and II (0.55 and 0.64; Oosterhoff 1939). This is also the case for the subsamples of RRc variables, having mean periods of 0.343 and 0.366, versus 0.32 and 0.37 for the OoI and OoII globular clusters of the Milky Way. On the other hand, the whole sets of RRab and RRc have mean periods of 0.604 and 0.353, respectively. These numbers would lead to the classification of Tucana as an Oosterhoff intermediate (Oo-Int), as is the case for most dSphs (Catelan 2004). In this particular case, however, there is the possibility that the Oo-Int status could be attributed to the mixture of OoI and OoII populations, as hinted by the two roughly parallel sequences in the P-A diagram of the RRab in Figure 2.

The presence of different populations in a galaxy, whether due to the details of its star formation history or to the accretion of an external stellar system, generally leads to gradients in the observable properties of its stars. Figure 3 presents the radial profile for each subsample of RR Lyrae stars. The radii were chosen so that each concentric region contains the same number of variables. It shows that, for each type of RR Lyrae stars, the fainter variables are systematically more concentrated near the center of the galaxy, while the brighter RR Lyrae stars are spatially extended. The difference in spatial distribution is very significant as the radii containing half of the bright and faint RR Lyrae stars are $1.33'$ and $1.09'$, respectively, and a KS test gives a probability of $\lesssim 0.001$ for the bright and faint RR Lyrae

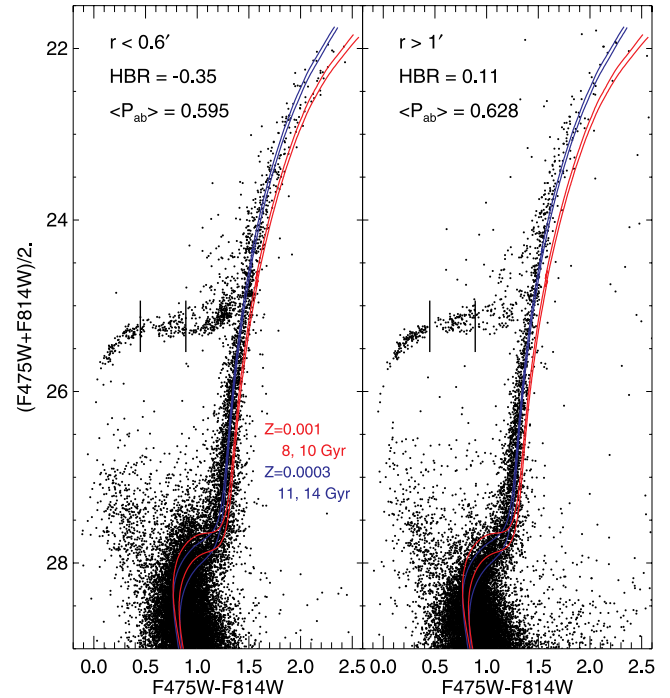


FIG. 4.—Color-magnitude diagrams of the inner and outer regions of Tucana, containing the same number of stars. The vertical lines delimit the IS. Isochrones from the BaSTI library (Pietrinferni et al. 2004), with ages and metallicities indicated in the figure, have been superimposed to highlight the gradients. Note the difference in the upper RGB, HB/red clump morphology and upper main sequence.

stars to have the same radial distribution. The combination of different intrinsic properties of the individual stars with the different spatial distribution supports the hypothesis that they represent separate populations.

4. DISCUSSION

The difference in the mean period of the RRab stars of each sample could be attributed to both a difference in metallicity (from the period-metallicity correlation) or a difference in the evolutionary status of the individual stars, the stars in the redward evolution off the ZAHB having a longer period (Bono et al. 1997b, their Figs. 16–17). However, the top panel of Figure 1 shows that evolution off the ZAHB alone cannot account for the range of luminosity spanned by the RR Lyrae stars. Hence, it is necessary to invoke a range of metallicity to reproduce the distribution of stars within the IS. The hypothesis of a bimodal metallicity distribution is strengthened by the double “bell shape” of the RRc in the P-A diagram (Bono et al. 1997a) and the presence of two RGB bumps separated by ~ 0.2 mag in F814W (C. Gallart et al. 2008, in preparation). We use the luminosity of the theoretical ZAHB in Figure 1 to estimate this range. A firm upper limit for the metallicity of the old population is given by the ZAHB at $Z = 0.001$. While the $Z = 0.0001$ ZAHB seems to be slightly too luminous, the $Z = 0.0003$ tracks cannot produce the brightest RR Lyrae stars in our observations. We suggest $Z \sim 0.0002$ as an approximate lower limit to the metallicity of Tucana.

Although the range of metallicity is relatively wide for a dSph, it is supported by the color of the RGB of the inner and outer regions of Tucana presented in Figure 4. The isochrones show that the higher metallicity population visible in the central region, with

$Z \sim 0.001$, is absent in the outer region, while a metallicity slightly lower than $Z = 0.0003$ is needed to explain the blue side of the sub-HB RGB. Note, also, the difference in the morphology of the HB. The faint RR Lyrae variables and the red HB stars show up only in the center of the galaxy, while the brighter stars of the IS and the blue HB stars are present everywhere. Consequently, the HB ratio (HBR¹²) increases by about 0.5 over the radius sampled with our data, similar to what was observed in the Sculptor dSph (Majewski et al. 1999; see also Hurley-Keller et al. 1999), for which spectroscopy indicates the presence of a metallicity gradient (Tolstoy et al. 2004) and a metallicity spread (Clementini et al. 2005) within the old (≥ 10 Gyr) HB population.

Our metallicity range supports the results of Harbeck et al. (2001) who found a bimodal [Fe/H] distribution in Tucana from the RGB stars over their observed *HST* WFPC2 field. From isochrones in the HB morphology-metallicity plane, they explain the gradient in HB morphology as a “pure metallicity effect.” However, artificial CMDs produced by IAC-STAR (Aparicio & Gallart 2004)¹³ show that to obtain a red HB component such as the one observed in the center of Tucana, stars having a total mass in the range $\sim 0.75\text{--}0.80 M_{\odot}$ are needed (see also Fig. 1, top). Assuming the common value for the mass-loss parameter $\eta = 0.40$ with the BaSTI library (Pietrinferni et al. 2004), these masses correspond to stars younger than about 9 Gyr old, quite independently of the metallicity between $Z = 0.0001$ and 0.001. The same models give an age of ~ 13 Gyr for the bluest HB stars at $Z = 0.0001$ which are present over the whole galaxy.

The morphology of the MSTO in Figure 4 reflects this range of age: one can see that the CMD of the central region harbors a younger population than the outer region. Fitting isochrones to the subgiant branch gives a population age ranging from about 11 to 14 Gyr old in the outer part of the galaxy, while it appears to be as young as ~ 8 Gyr in the center. Note that crowding tends to broaden the features in a CMD and may be partly decreasing the estimated age of the youngest MSTO stars in the center of the galaxy. Nonetheless, a preliminary SFH of the inner and outer regions of Tucana—which takes into account the effects of crowding—do show that there is a slightly younger population in the center.

However, the youngest stars *within* the IS are slightly older than the red HB stars. Figure 5 illustrates the results of our artificial HB computations: it represents the mean mass as a function of age and metallicity for artificial stars within the IS

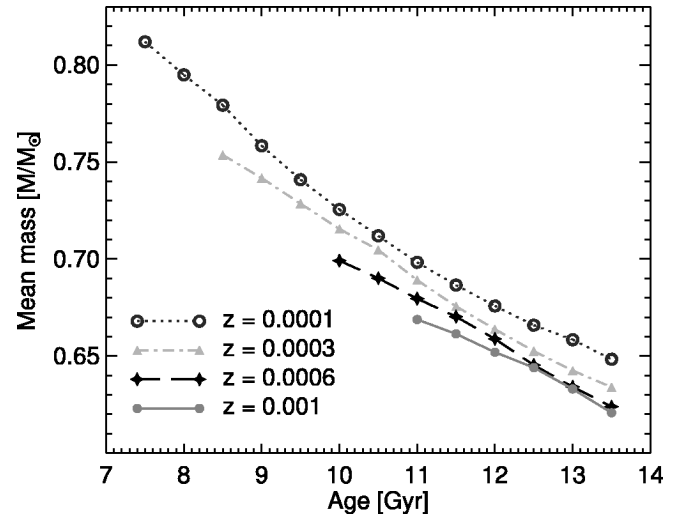


FIG. 5.—Mean mass as a function of age and metallicity for artificial stars within the IS of Tucana, from IAC-STAR simulations using the BaSTI library with $\eta = 0.4$ (Pietrinferni et al. 2004) and no dispersion in mass loss at a given age. [See the electronic edition of the Journal for a color version of this figure.]

of Tucana, and indicates that the faintest, highest metallicity ($Z \geq 0.0006$) variables of Tucana must be ≥ 10 Gyr old. *Therefore, under the reasonable assumption that chemical enrichment follows age in star-forming galaxies, the presence of gradients in the RR Lyrae populations shows that these metallicity gradients appeared very early on in the history of this galaxy.*

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Facilities: HST(ACS)

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